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GIS-Based Assessment of Urbanization Impact on Groundwater Resources in a Rapidly Urbanizing Region of Hyderabad, India

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Abstract: *Rapid urbanization has significantly altered groundwater recharge processes, leading to aquifer depletion and groundwater quality deterioration in many regions of India. Expansion of impervious surfaces and land use changes have reduced natural recharge and increased pressure on groundwater resources. This study employs Geographic Information System (GIS) and remote sensing techniques to investigate the impact of urbanization on groundwater resources through the analysis of land use/land cover (LULC) changes, groundwater level variations, and hydrochemical characteristics. Multi-temporal satellite datasets, including Landsat-8, Sentinel-2, and MODIS imagery, are utilized to derive spatial indicators such as the Normalized Difference Vegetation Index (NDVI), built-up index, and surface imperviousness. Groundwater monitoring records and hydrochemical data obtained from the Central Ground Water Board (CGWB) are incorporated for validation and trend analysis. The results indicate a substantial increase in urban built-up areas accompanied by a decline in vegetation cover and recharge potential, resulting in intensified groundwater stress and localized groundwater quality deterioration in several urban clusters. According to the Dynamic Ground Water Resource Assessment Report 2024, 751 out of 6746 assessment units (11.13%) are categorized as over-exploited, while 206 and 711 units are classified as critical and semi-critical, respectively. The findings demonstrate a strong relationship between urban expansion and groundwater stress and highlight the effectiveness of GIS-based spatial modeling in identifying recharge-loss zones and vulnerable aquifer systems. The study emphasizes the need for sustainable urban planning, artificial recharge measures, rainwater harvesting, and integrated groundwater resource management strategies to ensure long-term water security and groundwater sustainability.*

Keywords: Groundwater, GIS, Urbanization, Land Use/Land Cover (LULC), Remote Sensing, NDVI, Groundwater Recharge, Hydrogeology, Water Quality.

1. Introduction

Groundwater is one of the most important natural resources and serves as a major source of freshwater for domestic, agricultural, industrial, and ecological requirements. Nearly half of the global population depends on groundwater for drinking purposes, while a significant portion of irrigated agriculture relies on groundwater resources. In India, groundwater constitutes the backbone of water supply systems and plays a vital role in ensuring food security, economic development, and urban growth. However, increasing population, industrialization, and rapid urban expansion have imposed substantial pressure on groundwater resources, resulting in declining water tables and deterioration of groundwater quality.

Urbanization is a major driver of environmental change and significantly alters the natural hydrological cycle. The expansion of urban areas involves extensive modifications in land use and land cover (LULC), leading to the replacement of vegetation and permeable soil surfaces with impervious materials such as roads, buildings, and pavements. These changes reduce infiltration and groundwater recharge while increasing surface runoff and the occurrence of urban flooding. Moreover, increasing domestic, industrial, and commercial water demand has accelerated groundwater extraction beyond sustainable limits in many urban regions.

The adverse impacts of urbanization on groundwater systems are particularly pronounced in developing countries, where rapid and often unplanned growth has altered natural recharge mechanisms and increased stress on aquifer systems. Excessive abstraction, coupled with reduced recharge, has resulted in groundwater depletion, land subsidence, and deterioration of water quality. Groundwater resources are also becoming increasingly vulnerable to contamination from domestic sewage, industrial effluents, agricultural chemicals, and improper waste disposal. Elevated concentrations of total dissolved solids (TDS), nitrates, heavy metals, and microbial contaminants have been reported in several urban aquifers, posing serious risks to public health and environmental sustainability.

India is one of the largest users of groundwater in the world and faces significant challenges associated with groundwater depletion. According to the Dynamic Ground Water Resource Assessment Report 2024 published by the Central Ground Water Board (CGWB), the annual groundwater recharge in India is estimated at 446.90 billion cubic meters (BCM), while annual groundwater extraction is about 245.64 BCM, corresponding to an overall stage of groundwater extraction of 60.47%. Among the 6746 assessment units, 751 units (11.13%) are categorized as over-exploited, whereas 206 and 711 units are classified as critical and semi-critical, respectively. Although groundwater conditions have improved in some regions owing to conservation measures and artificial recharge initiatives, rapid urbanization and excessive abstraction continue to threaten groundwater sustainability.

Land use and land cover changes are among the primary factors influencing groundwater recharge and groundwater quality. Conversion of agricultural lands, forests, wetlands, and open spaces into built-up areas significantly modifies the hydrological characteristics of a region. Increasing

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impervious surfaces restrict rainwater infiltration and reduce aquifer replenishment, resulting in declining groundwater storage and increasing water stress. Climate variability and changing rainfall patterns further aggravate groundwater scarcity by affecting recharge processes and increasing the frequency of droughts and extreme weather events.

Conventional hydrogeological investigations are often time-consuming and expensive, requiring extensive field surveys and monitoring programs. In recent decades, Geographic Information Systems (GIS) and remote sensing technologies have emerged as powerful tools for groundwater assessment and management. Satellite platforms such as Landsat-8, Sentinel-2, and MODIS provide valuable information for monitoring urban expansion and environmental changes. Spectral indices including the Normalized Difference Vegetation Index (NDVI), Normalized Difference Built-up Index (NDBI), and impervious surface indices are widely used to characterize land cover dynamics and evaluate their influence on groundwater resources.

GIS facilitates the integration of multiple thematic layers, including geology, geomorphology, soil characteristics, rainfall, drainage density, slope, and land use information, thereby providing a comprehensive framework for groundwater potential mapping and recharge zone identification. In addition, hydrochemical investigations involving parameters such as pH, electrical conductivity, total dissolved solids, chloride, sulfate, nitrate, and fluoride provide valuable information regarding groundwater quality and contamination processes. The integration of hydrochemical analysis with GIS and remote sensing techniques enables a comprehensive understanding of groundwater resource dynamics and supports effective management strategies.

The increasing availability of high-resolution satellite imagery and advanced geospatial technologies has greatly enhanced the capability to monitor groundwater-related changes and predict future scenarios. GIS-based spatial modeling enables the identification of groundwater depletion hotspots, recharge-loss zones, and vulnerable aquifer systems, thereby supporting sustainable groundwater management practices, artificial recharge structures, rainwater harvesting systems, and integrated urban planning policies.

Therefore, the present study aims to evaluate the impact of urbanization on groundwater resources using GIS and remote sensing techniques. The study focuses on analyzing land use and land cover changes, assessing groundwater level variations, investigating hydrochemical characteristics, and identifying groundwater stress zones and recharge-loss areas.

The integration of geospatial technologies with hydrogeological information is expected to provide valuable insights for sustainable groundwater management and support decision-making processes related to urban planning, water conservation, and integrated water resource management, thereby contributing to long-term groundwater sustainability and water security.

2. Literature Survey

Groundwater depletion and groundwater quality deterioration have become major environmental concerns due to rapid urbanization, excessive groundwater abstraction, and climate variability. Recent assessments by the Central Ground Water Board (CGWB) indicate that groundwater stress persists in several regions of India despite improvements achieved through artificial recharge and water conservation measures. Urbanization has been identified as one of the major drivers of groundwater depletion. Kumar et al. (2021) reported that increasing impervious surfaces and rapid urban expansion significantly alter the natural hydrological cycle by reducing infiltration and enhancing surface runoff. Similarly, Dangar et al. (2023) emphasized that excessive groundwater abstraction and land use transformation have intensified groundwater stress and reduced aquifer sustainability in many parts of India. Remote sensing and Geographic Information Systems (GIS) have emerged as effective tools for groundwater investigations. ISRO (2023) highlighted the importance of satellite-based observations for water resource assessment, whereas NASA Earth Observatory (2024) demonstrated the capability of Landsat imagery in monitoring urban expansion and land use/land cover (LULC) changes. Lillesand and Kiefer (2023) further emphasized the usefulness of remote sensing techniques for analyzing spatial and temporal variations in environmental and hydrological systems.

Groundwater depletion is a global issue. Davis et al. (2021) reported substantial groundwater losses worldwide due to population growth, agricultural intensification, and urban development. UNESCO (2023) and UN-Water (2024) stressed the importance of integrated water resource management practices for ensuring long-term water sustainability, while the World Bank (2022) highlighted the need for improved groundwater governance and monitoring strategies. Climate variability also plays an important role in groundwater dynamics. Swain et al. (2022) showed that changes in precipitation patterns significantly influence groundwater recharge and availability. Likewise, Davamani et al. (2024) reported that increasing temperatures and extreme climatic events are likely to intensify groundwater stress in vulnerable regions. Recent advances in machine learning and data-driven techniques have enhanced groundwater assessment capabilities. Seifi et al. (2020) demonstrated the effectiveness of machine learning algorithms for groundwater level prediction and forecasting. In addition, several studies have shown that changes in land use and land cover considerably influence groundwater recharge and hydrological processes. Mondal and Ajaykumar (2022) emphasized the importance of spatial analysis for sustainable groundwater utilization, while Burrough and McDonnell (2020) highlighted the capability of GIS for integrating multiple thematic layers in environmental applications.

Recent reports published by NITI Aayog (2023), the Central Water Commission (2023), and the Ministry of Housing and Urban Affairs (2024) indicate that increasing population, industrialization, and urban expansion are intensifying water stress in many Indian cities. These studies collectively demonstrate that the integration of GIS, remote sensing, hydrogeological investigations, and hydrochemical analysis provides an effective framework for groundwater assessment and sustainable water resource management.

2.1 Research Gap

Although numerous studies have investigated groundwater depletion using GIS and remote sensing techniques, most studies focus either on groundwater quantity or groundwater quality independently. Limited attention has been devoted to the integrated analysis of land use/land cover changes, groundwater level fluctuations, and hydrochemical characteristics within a unified framework. Furthermore, the combined use of multi-temporal satellite imagery, spatial interpolation techniques, and hydrochemical investigations for identifying groundwater depletion hotspots and recharge-loss zones has received relatively little attention. Therefore, there is a need for a comprehensive GIS- and remote sensing-based approach that integrates land use analysis, groundwater level assessment, and hydrochemical characterization to support sustainable groundwater resource management under increasing urbanization pressure.

3. Proposed Methodology

The proposed methodology integrates Geographic Information System (GIS), remote sensing techniques, hydrogeological investigations, and hydrochemical analysis to evaluate the impact of urbanization on groundwater resources. Multi-temporal satellite data obtained from Landsat-8, Sentinel-2, and MODIS are utilized to analyse land use and land cover (LULC) changes, vegetation dynamics, and urban expansion, while groundwater level and hydrochemical data obtained from the Central Ground Water Board (CGWB) and field observations are used to assess groundwater quantity and quality.

Initially, satellite images are pre-processed through radiometric, atmospheric, and geometric corrections, followed by image enhancement and band stacking to improve image quality. Supervised LULC classification is then performed to identify built-up areas, vegetation, agricultural land, water bodies, and barren land. Temporal LULC maps are generated to evaluate urban growth patterns and their influence on groundwater recharge.

To characterize vegetation and urbanization patterns, spectral indices such as the Normalized Difference Vegetation Index (NDVI) and Normalized Difference Built-up Index (NDBI) are derived from satellite imagery. These indices provide information regarding vegetation cover, urban expansion, and surface imperviousness, which directly influence groundwater recharge processes. The generated thematic layers are integrated within a GIS environment for spatial analysis.

Groundwater level data collected from observation wells are analysed to determine temporal variations in water table depth. Spatial interpolation techniques, including Inverse Distance Weighting (IDW) and Kriging, are employed to generate groundwater contour maps and identify regions experiencing groundwater depletion. In addition, hydro-chemical parameters such as pH, electrical conductivity, total dissolved solids, total hardness, chloride, sulphate, nitrate, and fluoride are analysed to evaluate groundwater quality and determine its suitability for domestic and agricultural purposes.

Various thematic layers, including LULC, NDVI, NDBI, groundwater level, rainfall, slope, drainage density, and hydro-chemical parameters, are integrated using GIS-based weighted overlay analysis to delineate groundwater vulnerability zones. The spatial analysis facilitates the identification of groundwater stress regions, recharge-loss zones, and vulnerable aquifer systems. The final outputs include land use maps, vegetation maps, groundwater contour maps, hydro-chemical distribution maps, recharge zone maps, and groundwater vulnerability maps, which provide valuable decision-support information for sustainable groundwater management and integrated urban planning.

3.1 Methodological Framework

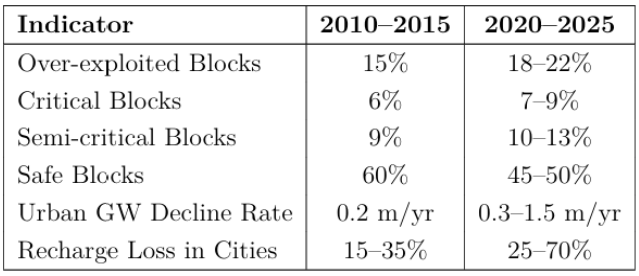
The proposed framework consists of the following stages:

1) Data acquisition and preprocessing of satellite imagery and field data.
2) Land Use/Land Cover (LULC) classification using multi-temporal satellite images.
3) Extraction of vegetation and built-up indices (NDVI and NDBI).
4) Groundwater level analysis using observation well data.
5) Hydrochemical analysis for groundwater quality assessment.
6) Spatial interpolation and GIS-based mapping using IDW and Kriging techniques.
7) Identification of groundwater depletion hotspots and stress zones.
8) Preparation of groundwater recharge and vulnerability maps through weighted overlay analysis.

3.2 Novelty of the Proposed Methodology

Unlike previous studies that primarily focus on either groundwater quantity or groundwater quality, the proposed framework integrates multi-temporal remote sensing data, groundwater level observations, hydrochemical characteristics, and GIS-based spatial analysis within a unified platform. This integrated approach enables the identification of groundwater depletion hotspots, recharge-loss regions, and vulnerable aquifer systems, thereby providing an effective decision-support framework for sustainable groundwater resource management under increasing urbanization pressure.

Table 1: groundwater conditions in India



Indicator	2010–2015	2020–2025
Over-exploited Blocks	15%	18–22%
Critical Blocks	6%	7–9%
Semi-critical Blocks	9%	10–13%
Safe Blocks	60%	45–50%
Urban GW Decline Rate	0.2 m/yr	0.3–1.5 m/yr
Recharge Loss in Cities	15–35%	25–70%

Table.1 summarizes the changes in groundwater conditions in India between 2010–2015 and 2020–2025. The results indicate increasing groundwater stress, characterized by a rise in over-exploited, critical, and semi-critical blocks and a corresponding decline in safe blocks. Urban groundwater depletion rates have increased from approximately 0.2 m/year to 0.3–1.5 m/year, while groundwater recharge losses have intensified from 15–35% to 25–70% due to rapid urbanization and expansion of impervious surfaces. These trends demonstrate a growing imbalance between groundwater extraction and natural recharge, highlighting the urgent need for sustainable groundwater management and artificial recharge measures. As shown in **Fig. 1**, rapid urbanization and land use changes during 2010–2025 have significantly influenced groundwater resources. Multi-temporal Land Use/Land Cover (LULC) analysis reveals a substantial expansion of built-up areas accompanied by a decline in vegetation and agricultural lands. The increase in impervious surfaces has reduced natural infiltration and groundwater recharge while enhancing surface runoff, thereby altering the hydrological balance.

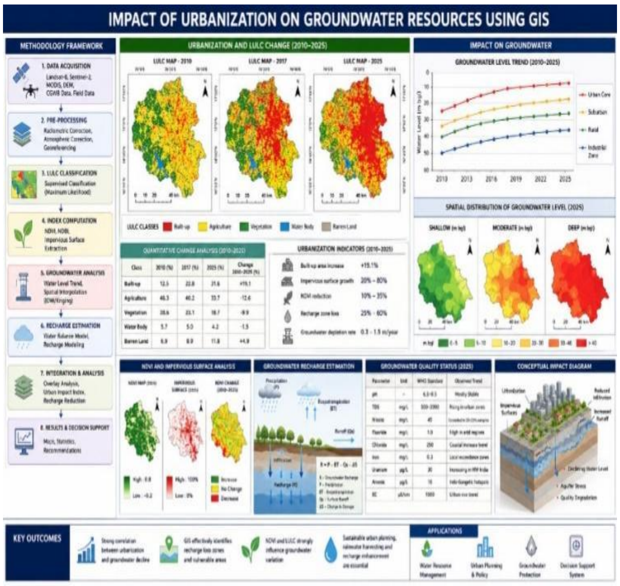


Figure 1: Testing data- load current (amperes)

The groundwater level trend analysis presented in **Fig. 1** indicates a continuous decline in groundwater levels, with severe depletion observed in urban core and industrial regions. In contrast, rural and vegetated areas exhibit relatively stable groundwater conditions due to higher recharge potential. Spatial groundwater distribution maps further show that deep groundwater zones are predominantly concentrated in densely urbanized regions, indicating elevated groundwater stress. The NDVI and impervious surface analyses establish a strong relationship between vegetation loss, urban expansion, and groundwater depletion. The results indicate a considerable increase in built-up area and impervious surface coverage, accompanied by a reduction in vegetation cover and recharge zones, thereby adversely affecting groundwater availability and aquifer sustainability.

Groundwater quality analysis reveals increasing concentrations of total dissolved solids (TDS), nitrate, chloride, and electrical conductivity in urban and industrial areas, indicating progressive deterioration in groundwater quality. The integration of hydrochemical parameters with GIS-based spatial analysis effectively identifies contamination hotspots and vulnerable aquifer regions. Furthermore, the recharge estimation and conceptual analysis illustrated in **Fig. 1** demonstrate that uncontrolled urban development reduces infiltration and groundwater recharge while increasing surface runoff, ultimately resulting in aquifer stress, declining groundwater levels, and groundwater quality degradation. The results confirm that the integration of GIS, remote sensing, hydrogeological investigations, and spatial interpolation techniques provides an effective framework for identifying groundwater depletion hotspots and recharge-loss zones.

3.3 Mathematical Modeling

The mathematical framework integrates hydrological balance equations, Darcy-based groundwater flow principles, and GIS-derived urbanization indices to quantify the impact of urban expansion on groundwater resources. The proposed models describe recharge mechanisms, groundwater flow characteristics, urbanization pressure, runoff generation, and groundwater stress conditions.

1) *Groundwater Recharge Model*

Groundwater recharge is estimated using the water balance equation:

$$R = P - ET - Qs - \Delta S$$

where:

- R = Groundwater recharge (mm/year)
- P = Annual precipitation (mm/year)
- ET = Evapotranspiration (mm/year)
- Qs = Surface runoff (mm/year)
- ΔS = Change in soil moisture storage

This model represents the amount of water available for aquifer replenishment after accounting for losses due to evapotranspiration, runoff, and soil storage changes.

2) *Recharge Coefficient Model*

The recharge coefficient is defined as

$$Rc = R/P$$

where Rc represents recharge efficiency.

Region	Recharge Coefficient
Urban areas	0.05–0.25
Semi-urban areas	0.20–0.45
Rural areas	0.40–0.65

Lower recharge coefficients indicate reduced infiltration caused by impervious surfaces.

3) *Darcy's Law for Groundwater Flow*

Groundwater flow through porous media is governed by Darcy's law:

$$Q = -KA(dh/dl)$$

where:

- Q = Groundwater discharge (m^3/day)
- K = Hydraulic conductivity (m/day)
- A = Cross-sectional area (m^2)
- dh/dl = Hydraulic gradient

This equation describes groundwater movement within aquifers.

4) Urban Impact Index (UII)

Urbanization pressure is quantified using

$$\text{UII} = \text{A built-up} / \text{Atotal}$$

where

- Abuilt-up = Built-up area
- Atotal = Total study area

Urban Impact Index	Impact Level
$\text{UII} < 0.3$	Low impact
$0.3 \leq \text{UII} \leq 0.6$	Moderate impact
$\text{UII} > 0.6$	High impact

Higher UII values indicate greater urban influence and reduced groundwater recharge.

5) Runoff Coefficient Model

The runoff coefficient is expressed as

$$Cr = Qs/P$$

Where

- Cr = Runoff coefficient
- Qs = Surface runoff
- P = Precipitation

Land Type	Runoff Coefficient
Vegetated regions	0.1–0.3
Mixed land use	0.3–0.6
Urban impervious areas	0.6–0.95

Higher runoff coefficients indicate lower infiltration capacity.

6) Recharge Reduction Model

Recharge reduction due to urbanization is estimated as

$$RR = 1 - (Rurban/Rnatural)$$

where

- Rurban = Recharge under urban conditions
- Rnatural = Natural recharge

Large values of RR represent severe reduction in aquifer replenishment caused by urban development.

7) Groundwater Stress Index (GSI)

A groundwater stress indicator is defined as

$$GSI = D/Rc$$

where

- D = Groundwater demand
- Rc = Recharge coefficient

GSI Value	Groundwater Condition
$\text{GSI} < 1$	Sustainable
$\text{GSI} \approx 1$	Critical
$\text{GSI} > 1$	Over-exploited

This index provides a measure of the balance between groundwater demand and recharge.

8) Groundwater Level Decline Model

The change in groundwater level is represented by

$$\Delta h = (Qpump - R)/S$$

Where

- Δh = Groundwater head variation
- Qpump = Pumping rate
- R = Recharge
- S = Specific yield

Increasing pumping rates and decreasing recharge result in groundwater level decline.

9) GIS-Based Weighted Impact Index

To integrate multiple spatial factors influencing groundwater, a weighted index is formulated as

$$WII = w1(UII) + w2(NDVI) + w3(Rc) + w4(Cr)$$

Where

- UII = Urban Impact Index
- NDVI = Normalized Difference Vegetation Index
- Rc = Recharge coefficient
- Cr = Runoff coefficient
- wi = Corresponding weights

Parameter	Weight
Urban Impact Index (UII)	0.35
NDVI	0.25
Recharge coefficient	0.25
Runoff coefficient	0.15

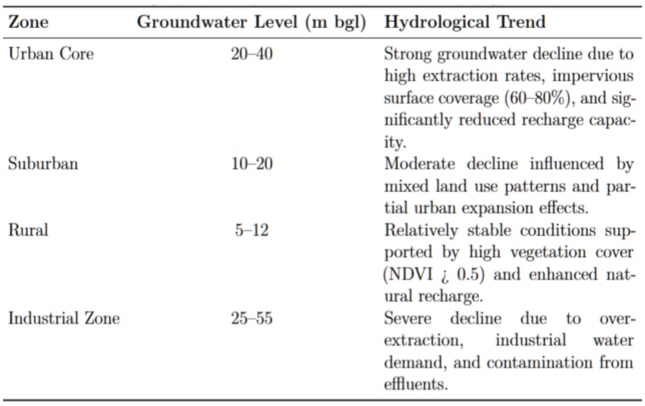
The weighted impact index facilitates the identification of groundwater stress zones and recharge-loss regions.

3.4 Results Analysis

The spatial analysis reveals significant variations in groundwater conditions across different land use zones. Urban and industrial regions characterized by extensive built-up areas and high impervious surface coverage exhibit reduced recharge potential and elevated groundwater stress compared with rural and vegetated areas. Groundwater contour maps and hydrochemical analyses indicate that densely urbanized regions experience severe groundwater depletion and progressive water quality deterioration, whereas vegetated regions maintain relatively stable groundwater conditions owing to higher infiltration and recharge capacity. Furthermore, the integrated analysis of land use changes, vegetation indices, recharge characteristics, and hydrochemical parameters establishes a strong relationship between urbanization intensity and groundwater degradation. These findings highlight the importance of sustainable urban planning, rainwater harvesting, artificial recharge structures, and integrated water resource management strategies to ensure long-term groundwater sustainability and water security.

3.5 Spatial and Hydrological Interpretation

Table 2: Groundwater Across Different Land Use Zones



Zone	Groundwater Level (m bgl)	Hydrological Trend
Urban Core	20–40	Strong groundwater decline due to high extraction rates, impervious surface coverage (60–80%), and significantly reduced recharge capacity.
Suburban	10–20	Moderate decline influenced by mixed land use patterns and partial urban expansion effects.
Rural	5–12	Relatively stable conditions supported by high vegetation cover (NDVI ¿ 0.5) and enhanced natural recharge.
Industrial Zone	25–55	Severe decline due to over-extraction, industrial water demand, and contamination from effluents.

Industrial areas experience the most severe groundwater stress due to intensive groundwater extraction coupled with contamination from industrial effluents, resulting in both quantitative depletion and deterioration of water quality. Suburban regions exhibit intermediate characteristics and act as transitional zones, experiencing moderate reductions in recharge and groundwater availability. Overall, the spatial distribution patterns indicate that groundwater depletion and quality degradation are closely associated with urbanization intensity, impervious surface expansion, and anthropogenic activities, highlighting the importance of sustainable land use planning, artificial recharge measures, and integrated groundwater management strategies for ensuring long-term water resource sustainability.

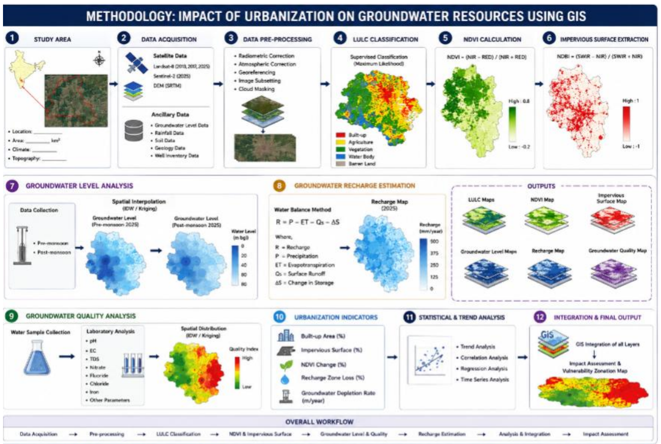


Figure 2: Methodology Framework

3.6 Methodology Analysis

As shown in **Fig. 2**, the proposed methodology provides a comprehensive framework for assessing the impact of urbanization on groundwater resources using Geographic Information Systems (GIS), remote sensing techniques, hydrogeological investigations, and statistical analysis. The framework integrates satellite imagery, groundwater observations, hydrochemical measurements, and ancillary geospatial datasets to facilitate a systematic evaluation of groundwater quantity and quality.

The methodology consists of sequential stages, including study area selection, data acquisition, image preprocessing, Land Use/Land Cover (LULC) classification, vegetation index computation, impervious surface extraction, groundwater level analysis, recharge estimation, groundwater quality assessment, and statistical evaluation. The integration of these components enables the development of GIS-based groundwater impact assessment and vulnerability maps.

Groundwater level analysis employs spatial interpolation techniques such as Inverse Distance Weighting (IDW) and Kriging to generate groundwater distribution maps and identify potential stress zones. Recharge estimation based on the water balance approach provides information regarding aquifer replenishment under varying land-use conditions. Hydrochemical analysis is incorporated to evaluate groundwater quality and assess contamination vulnerability.

Furthermore, urbanization indicators, including built-up area, impervious surface coverage, vegetation characteristics, recharge conditions, and groundwater variability, are integrated within a GIS environment to establish relationships between land-use transformation and groundwater dynamics. The combination of remote sensing, hydrogeological analysis, and statistical techniques provides an efficient decision-support framework for groundwater monitoring, vulnerability assessment, and sustainable urban planning.

Overall, the methodology illustrated in **Fig. 2** demonstrates that the integrated application of GIS, remote sensing, hydrogeological analysis, and spatial statistics provides a robust and scalable framework for groundwater assessment and long-term groundwater resource management under increasing urbanization pressure.

4. Major Components of the Proposed Methodology

1) Integration of GIS, remote sensing, hydrogeological investigations, and statistical analysis for comprehensive groundwater assessment.
2) Utilization of multi-source datasets, including satellite imagery, groundwater observations, rainfall records, and hydrochemical information.
3) Extraction of urbanization indicators through LULC classification, NDVI computation, and impervious surface mapping.
4) Groundwater level analysis using spatial interpolation techniques such as IDW and Kriging.
5) Recharge estimation based on water balance principles.
6) Hydrochemical investigations for groundwater quality evaluation and contamination assessment.
7) GIS-based integration of thematic layers for groundwater stress and vulnerability mapping.
8) Statistical analysis for understanding the relationship between urbanization and groundwater dynamics.
9) Development of a decision-support framework for groundwater resource management.
10) Applicability of the methodology to different urban and semi-urban environments.

Key Observations

- Urbanization alters groundwater recharge processes through changes in land use and impervious surface distribution.
- Comprehensive groundwater assessment requires the integration of satellite observations, field measurements, and hydrochemical analysis.
- Spatial interpolation techniques improve the visualization and interpretation of groundwater distribution patterns.
- Statistical analysis facilitates understanding of the relationship between urbanization indicators and groundwater dynamics.
- GIS-based thematic integration provides an effective decision-support tool for groundwater resource management.
- The proposed framework is capable of identifying vulnerable aquifer systems and supporting sustainable groundwater conservation strategies. These revised statements are fully consistent with the methodology shown in **Fig.2** and avoid presenting results that are not explicitly contained in the figure.

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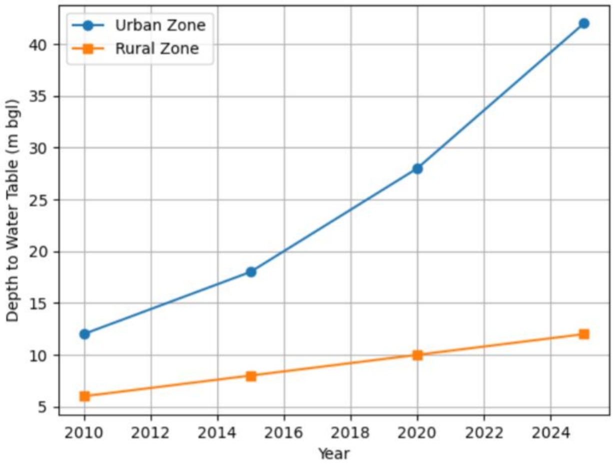

Figure 3: Groundwater level variation in urban and rural zones (2010–2025)

As illustrated in **Fig. 3**, groundwater levels exhibit distinct temporal variations in urban and rural regions during 2010–2025, demonstrating the influence of urbanization on groundwater resources. Urban areas show a significant increase in depth to the water table, from approximately 12 m below ground level (mbgl) in 2010 to nearly 42 mbgl in 2025, indicating severe groundwater depletion caused by increasing groundwater extraction and reduced recharge. In contrast, rural regions exhibit relatively stable groundwater conditions, with groundwater depth increasing gradually from about 6 mbgl to 12 mbgl over the same period owing to higher recharge potential and lower anthropogenic pressure.

The widening gap between urban and rural groundwater levels after 2015 indicates that rapid urban expansion, increasing impervious surface coverage, and growing water demand have accelerated groundwater depletion in urban environments. Conversely, greater vegetation cover and enhanced infiltration capacity have enabled rural areas to maintain comparatively stable groundwater conditions

5. Conclusion

The present study demonstrates a strong relationship between urbanization and groundwater depletion, confirming that land use transformation and increasing impervious surface coverage are major factors affecting aquifer sustainability. The integration of Geographic Information Systems (GIS), remote sensing techniques, and hydrogeological analysis provides an effective framework for assessing groundwater quantity and quality under changing urban environments. Highly urbanized regions exhibit greater groundwater stress, reduced recharge potential, and accelerated groundwater decline. Land Use/Land Cover (LULC) and vegetation analyses reveal that the conversion of vegetated and agricultural lands into built-up areas significantly alters natural hydrological processes by reducing infiltration and increasing surface runoff. Multi-temporal satellite datasets, including Landsat-8, Sentinel-2, and MODIS, effectively capture spatial and temporal variations in urban expansion and their impacts on groundwater resources. The results further demonstrate that GIS-based spatial modelling and interpolation techniques are highly effective in identifying groundwater depletion hotspots, recharge-loss zones, and vulnerable aquifer systems. Groundwater quality analysis indicates that urban and industrial regions are more susceptible to contamination and water quality deterioration due to increasing anthropogenic activities. The integration of thematic layers within a GIS environment facilitates the generation of groundwater vulnerability maps and provides a reliable decision-support framework for sustainable water resource management.

Overall, the findings emphasize the necessity of sustainable urban planning and integrated groundwater management practices, including artificial recharge structures, rainwater harvesting, protection of natural recharge zones, and controlled urban expansion. These measures are essential for mitigating groundwater depletion, preserving groundwater quality, and ensuring long-term water security in rapidly developing regions. Without appropriate interventions, continued urbanization and increasing water demand are likely to intensify groundwater stress and pose significant challenges to sustainable groundwater sustainability in the future.

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